

NASA CONTRACTOR REPORT

NASA-CR-195829

11/11/87  
11/22/87  
15P

# EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS

David W. Bogdanoff  
Jean-Luc Cambier  
Perikles Papadopoulos

Eloret Institute  
3788 Fabian Way  
Palo Alto, CA 94303

(NASA-CR-195829) EXPERIMENTAL  
INVESTIGATION OF NOZZLE/PLUME  
AERODYNAMICS AT HYPERSONIC SPEEDS  
Final Technical Report, 1 Aug. 1987  
- 31 Jan. 1994 (Eloret Corp.)  
15 p

N94-36687

Unclass

G3/02 0008435

Prepared for

Ames Research Center  
under Cooperative Agreement NCC2-487



National Aeronautics and  
Space Administration

**Ames Research Center**  
Moffett Field, California 94035

**NASA CONTRACTOR REPORT**

**EXPERIMENTAL INVESTIGATION  
OF NOZZLE/PLUME AERODYNAMICS  
AT HYPERSONIC SPEEDS**

David W. Bogdanoff  
Jean-Luc Cambier  
Perikles Papadopoulos

Eloret Institute  
3788 Fabian Way  
Palo Alto, CA 94303

**CONTRACT NAS2—**



1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS		5. Report Date 4/29/94	6. Performing Organization Code
		8. Performing Organization Report No.	
7. Author(s) David W Bogdanoff, Jean-Luc Cambier Perikles Papadopoulos		10. Work Unit No.	
9. Performing Organization Name and Address ELORET INSTITUTE 3788 Fabian Way Palo Alto, CA 94303		11. Contract or Grant No. NCC2-487	
		13. Type of Report and Period Covered 8/1/87 to 1/31/94	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C. 20456		14. Sponsoring Agency Code	
15. Supplementary Notes Point of Contact: Dr. David Bogdanoff, Dr. Jean-Luc Cambier c/o 230-2 NASA Ames Research Center, Moffett Field, CA 94035			
16. Abstract  The work performed by D. W. Bogdanoff, J.-L. Cambier, H. A. Zambrana, J. Dunn and P. Papadopoulos over the time period 1 August 1987 to 31 December 1993 is summarized briefly as follows. Much of the work involved the Ames 16 Inch Shock Tunnel facility. The facility was reactivated and upgraded, a data acquisition system was configured and upgraded several times, several facility calibrations were performed and test entries with a wedge model with hydrogen injection and a full scramjet combustor model, with hydrogen injection, were performed. Extensive CFD modelling of the flow in the facility was done. This includes modelling of the unsteady flow in the driver and driven tubes and steady flow modelling of the nozzle flow. Other modelling efforts include simulations of non-equilibrium flows and turbulence, plasmas, light gas guns and the use of non-ideal gas equations of state. New experimental techniques to improve the performance of gas guns, shock tubes and tunnels and scramjet combustors were conceived and studied computationally. Ways to improve scramjet engine performance using steady and pulsed detonation waves were also studied computationally. A number of studies were performed on the operation of the ram accelerator, including investigations of in-tube gasdynamic heating and the use of high explosives to raise the velocity capability of the device.			
17. Key Words (Suggested by Author(s)) 16-Inch shock tunnel scramjet combustor CFD flow modeling non-equilibrium flows		18. Distribution Statement  unclassified, unlimited	
19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of Pages	22. Price*

# EXPERIMENTAL INVESTIGATION OF NOZZLE/PLUME AERODYNAMICS AT HYPERSONIC SPEEDS

Final Technical Report

for  
Cooperative Agreement NCC2-487

for the period  
August 1, 1987 - January 31, 1994

Submitted to

National Aeronautics and Space Administration  
Ames Research Center  
Moffett Field, California 94035

Thermosciences Division  
Dr. Jim Arnold, Chief

Dr. George S. Deiwert, Technical Officer

Prepared by

ELORET INSTITUTE  
3788 Fabian Way  
Palo Alto, CA 94303  
Phone: (415) 493-4710  
Telefax: (415) 424-9876  
Dr. K. Heinemann, President and Grant Administrator  
Dr. David W. Bogdanoff, Principal Investigator  
Dr. J.-L. Cambier, Co-Principal Investigator  
Dr. P. Papadopoulos, Co-Principal Investigator

29 April, 1994

## Abstract

The work performed by D. W. Bogdanoff, J.-L. Cambier, H. A. Zambrana, J. Dunn and P. Papadopoulos over the time period 1 August 1987 to 31 December 1993 is summarized briefly as follows. Much of the work involved the Ames 16 Inch Shock Tunnel facility. The facility was reactivated and upgraded, a data acquisition system was configured and upgraded several times, several facility calibrations were performed and test entries with a wedge model with hydrogen injection and a full scramjet combustor model, with hydrogen injection, were performed. Extensive CFD modelling of the flow in the facility was done. This includes modelling of the unsteady flow in the driver and driven tubes and steady flow modelling of the nozzle flow. Other modelling efforts include simulations of non-equilibrium flows and turbulence, plasmas, light gas guns and the use of non-ideal gas equations of state. New experimental techniques to improve the performance of gas guns, shock tubes and tunnels and scramjet combustors were conceived and studied computationally. Ways to improve scramjet engine performance using steady and pulsed detonation waves were also studied computationally. A number of studies were performed on the operation of the ram accelerator, including investigations of in-tube gasdynamic heating and the use of high explosives to raise the velocity capability of the device.

## Introduction

The work performed by D. W. Bogdanoff, J.-L. Cambier, H. A. Zambrana, J. Dunn and P. Papadopoulos over the time period 1 August 1987 to 31 December 1993 is summarized herein. The work is divided into 8 different technical areas and summarized in the following 8 sections.

### 1. 16 Inch Shock Tunnel – Reactivation, Calibration, Upgrades, Testing, Data Acquisition System

A number of ideas have been developed and successfully applied to operation of the combustion driver of the facility. These include selection of a slightly oxygen-rich driver gas, use of a 2" diameter gas loading manifold in the driver tube, premixing He and O<sub>2</sub> before loading into the driver and waiting 2 hours from gas loading to ignition to allow improved gas mixing. It was also suggested that the Boeing on-the-fly gas mixing system be implemented to allow complete gas mixing of the fuel, oxidizer and diluent before they are injected into the driver. This technique should be implemented in 1994. A large amount of equipment has been designed and successfully used in the 16 Inch facility program. This includes transducer holders, instrumentation ports, pitot rake #1, 70 kHz amplifiers, the wedge model and its hydrogen fuel system, Pinckney probes, equipment to measure the ignition wire current and voltage, driver gas loading manifolds and the combustor model hydrogen fuel system.

A state-of-the-art data acquisition system (DAS) was designed for the facility. The implementation of the hardware and software used for the DAS was a pioneering effort. The lessons learned during the time the DAS system was developed were presented in Ref. 1 (May, 1991). (The material of Ref. 36 was also published as NASA TM 103849.) The DAS has been continually upgraded during 1989-1993 and, as of December, 1993, has 196 channels of 1 MHz digitizers with 100 channels of high quality instrumentation amplifiers. (Amplifiers are not needed for all types of data input.)

The following additional work was performed in the areas of data acquisition upgrade and model instrumentation improvement. The data transmission lines (standard 50 Ohm coaxial cable) from the driver, driven and nozzle section were upgraded in order to minimize the amount of RFI that appeared on much of the previous data. In this connection, it was essential to establish a new facility ground plane. A 35-head pitot and heat transfer probe rake (rake #2) was instrumented and installed at the exit plane of the facility nozzle in order to establish total pressure conditions of air entering the new test section. Pressure, heat transfer and skin friction gages on the scramjet model were installed and maintained during the first combustor test entry (September 1992 - March 1993).

Prior to the end of the first entry, planning had already been underway to modify the scramjet model for the second test entry. During the three month period between April 1993 and June 1993 design changes and instrument upgrades to the model were implemented. During the preparation for the second model entry, a new cowl inlet flow surface made of 17-4 PH stainless steel was designed to replace the previous flow surface which was made of 7075-T651 aluminum. The purpose for this modification was to improve the flow quality into the injector and combustor region by minimizing the amount of damage that the driver debris did to soft aluminum surfaces. Furthermore, the new design eliminated flow surface mounted fasteners. Also, during the preparation for the second model entry, the model instrumentation data bus was redesigned to accommodate approximately 40% more instrumentation.

A mass flow calibration device was designed to measure and confirm discharge coefficients of the hydrogen fuel injectors used in the first entry scramjet model. This experiment was performed in June, 1993, at NASA Ames' Transitional Flow Facility.

A series of publications allows the reactivation, calibration, upgrades and testing in the facility to be followed closely. These activities are reported below in sequence, with reference to the relevant publications. Reference 2 (October, 1989) describes the Ames 16 Inch Shock Tunnel and its operational techniques. The measurement techniques for obtaining static and impact pressures, shock velocities and optical data are outlined. Data is presented for runs at nozzle reservoir pressures of 60 bar. This data includes pressure histories from the combustion driver and nozzle reservoir. Tunnel clean-up procedures are described. Test section impact pressure and static pressure histories are presented. Nozzle static pressure and static temperature data are presented and compared with theoretical calculations. Test time estimates are given. Reference 3 (November, 1990) is an update of Ref. 2. Results are presented therein for operation of the tunnel at reservoir pressures of 280 and 350 bar. Tunnel operating conditions are compared with those of aerospace planes. Preliminary nozzle heat transfer data is presented. A design of a wedge model with provision for hydrogen fuel injection is described.

Reference 4 (April, 1991) presents data from operation of the facility at reservoir pressures up to 408 bar. Laser-based optical measurements (at 306 nm) of OH temperatures in the nozzle are presented. These and other data give estimated driver gas free test times of 3-5 msec for the facility. The wedge model fabrication has been completed at this point in time. A new test section, which is being designed is described. Reference 5 (January, 1992) discusses preliminary results from tests on the wedge model with hydrogen fuel injection at reservoir pressures of 270 and 408 bar. At this time, laser holographic interferograms has been taken of the flow over the model, the data acquisition system has been upgraded to 124 channels and the new test cabin has been fabricated and is being installed. Reference 6 (July, 1992) presents the data from the wedge model at Mach 14 enthalpy conditions. Runs were taken with no injection, with injection but no combustion (hydrogen injected into nitrogen) and with injection and combustion (hydrogen injected into air). The data presented included static pressures and heat flux rates on the wedge surface, pitot pressures at the trailing edge of the model and holographic interferograms taken parallel to the model surface. The experimental data were compared with CFD calculations and reasonably good agreement was found.

Reference 7 (July, 1992) presents a detailed characterization of the flow in the 16 Inch Shock Tunnel facility and the new test cabin. A new, high resolution rake, with pitot and stagnation point heat transfer heads, was installed at the nozzle exit for the calibration runs. The unsteady flow in the driver and driven tubes has been modelled with CFD calculations and excellent agreement between the theory and experimental measurements is shown. Detailed impact pressure surveys at the nozzle exit show a core flow about 60 cm wide, with impact pressures of ~4 bar at nozzle reservoir pressures of 408 bar. Measurements of nozzle static pressure and heat flux, test section static pressure, test section radiation and laser based static temperatures in the nozzle confirm driver gas free test times of 3-5 msec, for representative test conditions.

Reference 8 (January, 1994) presents possible options for upgrade of the facility. These are: (1) heating the driver gas with an electric heater to increase the driver pressure, (2) tapering the driven section to increase test gas pressure and enthalpy, (3) operating as a non-reflected shock tunnel and (4) operating as an expansion tube. Detailed computational modelling of the facility in these various configurations was carried out and the following conclusions drawn regarding simulation of scramjet combustor inlet conditions. Using reflected shock modes of operation, simulation is possible up to flight velocities of 3.5-5.4 km/sec with ideal test times of 3-20 msec and test section diameters of 100-150 cm. Expansion tube operation allows simulation of flight velocities up to 8 km/sec, ideal test times of 0.5-2.7 msec and

test section diameters of 30 cm (direct connect) and 100 cm (with attached nozzle). Using the non-reflected shock tunnel mode of operation, simulation was possible up to flight velocities of  $\sim 5$  km/sec with test times of  $\sim 1$  msec, a test section diameter of 50 cm and arguably, the most uniform, cleanest flow.

## 2. 16 Inch Shock Tunnel – CFD Modelling of Flow

We first describe the steady flow modelling effort. The supersonic nozzle flow in the 16 Inch Shock Tunnel facility used for hypersonic studies was investigated numerically. Three different nozzle contours (for operation at Mach 12, 14 and 16) were considered. The physical domain, extending from the end of the driven tube to the nozzle exit, was computed using a viscous multiple grid. The detailed driven tube end wall shield plate and nozzle geometries were also modeled. A set of nominal stagnation conditions for the nozzle was initially used. The nozzle flow field was computed using the experimentally prescribed driven tube stagnation conditions of  $P_o = 360$  bar and  $T_o = 5900$  K. A constant nozzle wall temperature,  $T_w$ , of 300 K was assumed. Real-gas chemistry was implemented using a multiple species air model including ionization. The following seven dominant species were considered: N, O, N<sub>2</sub>, O<sub>2</sub>, NO, NO<sup>+</sup>, e<sup>-</sup>.

Numerical simulations of the hypersonic environment of the 16 Inch Shock Tunnel nozzle were performed using a finite volume TVD code (MOZART) developed by J.-L. Cambier. Multiple grids have been used to study the effects of geometry at the driven tube end shield plate and nozzle inlet. Non-isentropic processes such as viscous boundary layer development and real-gas chemistry are included. Turbulence modeling was applied to capture boundary layer growth through the nozzle.

The nozzle flow was computed for the nominal flow conditions indicated earlier. Both laminar and turbulent solutions were obtained. The flow quantities were determined in the computational domain including both exit conditions and nozzle centerline properties. The effective area ratio, displacement thickness and momentum thickness were also determined. The obtained computations resulted in nozzle exit pitot pressures not in good agreement with the experimentally measured values. This is attributed to the uncertainties in the experimental data and possible effects of geometric discontinuities in the nozzle. It has been observed that in the vicinity of the junction between the nozzle cap and the main nozzle block (where the secondary diaphragm is located) there is a change in slope due to local ablation of the nozzle wall material. Such geometric discontinuities could induce boundary layer separation and since they are located close to the nozzle throat they could change the effective nozzle area ratio, thus affecting the nozzle exit flow conditions.

The inlet of the combustor model in the test chamber is located near the nozzle exit. The calculated nozzle exit flow conditions were used to obtain preliminary 2-D combustor model inlet calculations.

Reference 9 (June, 1990) presents a computational study of non-equilibrium H<sub>2</sub>-air reactions in the Ames facility nozzle. A nitrogen-water vapor mixture simulating hydrogen-air combustion products is produced and expanded in the facility nozzle. The number density of OH was measured along the nozzle using a laser absorption technique. The observed concentrations of OH are compared with those calculated using the conventional one-temperature reaction rate model and a two-temperature model accounting for the deviation of the vibrational-rotational temperature of hydrogen-bearing molecules from the translational temperature. The paper is a preliminary report on this study. Based on the two sets of available experimental data, the measured OH concentrations are smaller than those calculated by the existing one-temperature reaction model, even when the reaction rate coefficients are multiplied by a factor



of 10. The values calculated by the two-temperature model bound the experimental values under one operating condition, but fail to do so in the other. Therefore, the study thus far is inconclusive about the cause of the discrepancy between the experiment and the calculation. However, the study established the existence of a significant test time, cleanliness of the facility, and the computational ability to characterize the two-temperature nonequilibrium phenomena.

We now turn to simulations of unsteady flow in the facility. Reference 10 (July, 1992) investigates numerically various aspects of the 16 Inch Shock Tunnel operation. The development and propagation of the shock in the nozzle is first modeled: the resulting shock pattern qualitatively agrees with other experiments, and the propagation speed is correctly reproduced. The steady profiles at the nozzle exit agree with results from 1D codes. Sensitivity of the radiation signature to boundary layer thickness is obtained. Some aspects of shock reflection and interaction in the driven tube lead to important observations on the correct numerical techniques to use for these types of flows. The primary diaphragm rupture is also studied: this work shows that while the shock becomes planar rapidly, the contact discontinuity does not. Reference 11 (June, 1993) is a validation study of the code MOZART, used for simulation of unsteady phenomena in the 16 Inch Shock Tunnel. Two calculations were performed and compared to the experimental results. The agreement between the CFD calculations and experimental results is excellent.

### 3. CFD Modelling – Non – Equilibrium Flows and Turbulence, Plasmas, Non – Ideal Gas Equations of State; Light Gas Guns

The discussion in this section will largely follow the sequence of published papers, except for the very latest work which has not yet been published. Reference 12 (June, 1989) is the group's first paper on the development of a new code for flows in thermal non-equilibrium. The code uses a new and more accurate description of the thermo-chemical state of the gas, based on first principles. Validation of the code is presented. Numerical tests also show accuracy and robustness for stiff conditions.

Reference 13 (July, 1989) presents an inviscid fluid dynamics code that can handle multiple component species, a completely general equation of state, and velocities up to hundreds of kilometers per second. The code is third-order accurate in space and second-order accurate in time. First- and second-order Godunov procedures are used to calculate the cell boundary fluxes. The code was proofed with shock tube problems at pressure ratios up to  $10^4$ , impacts of ideal-gas and dense media zones at closing velocities up to 220 km/sec, detonation waves in  $H_2-O_2$  mixtures, ideal gas wedge and cone flows and a wedge flow of iron at 110 km/sec. Excellent agreement was found between the code CFD solutions and exact benchmark solutions.

Reference 14 (June, 1990) is a continuation of the work of Ref. 12 on non-equilibrium code development. Three codes are developed and tested. The first is for single-fluid, neutral plasma in thermochemical non-equilibrium. The second is for multi-fluid plasma and the third one is for ideal MHD plasmas. All codes rely on a conservative TVD scheme. The first code includes radiative processes, computed time-accurately with all collisional processes in the plasma. The second includes computation of the electric field induced by charge separation. The third involves a new TVD scheme based on the MHD characteristics. Reference 15 (June, 1991) is a validation study of the non-equilibrium (single fluid) plasma code. Numerical simulations are made of unsteady propagation of an ionizing shock in Argon. Simulations include all collisional and radiative processes, as well as radiation transport (1D), coupled time-accurately. The paper validates the code, and is able to reproduce unsteady, periodic

fluctuation phenomena observed experimentally.

Reference 16 (July, 1992) is a numerical study of various implicit numerical techniques for computation of reacting shock layers and nozzle flows. The study demonstrates that the so-called fully-coupled method is occasionally less stable than the loosely-coupled (explicit coupling) method. For stiff problems, all methods fail for large time steps. For  $CFL < 2$ , the scalar tri-diagonal method is as accurate than the  $N \times N$  block tri-diagonal method, and considerably less expensive. The relationship between solution accuracy and grid adaption was also studied. Reference 17 (July, 1993) presents an analysis of the convective heating expected for the space probe "Rosetta", during re-entry into earth's atmosphere. The conditions are extreme (16 km/sec, 0.5 atm stagnation pressure). Calculations were performed with chemical kinetics, to verify the degree of chemical non-equilibrium. Sensitivity studies with respect to grid spacing were performed. Three cases of catalyticity of the wall were also performed. Convective heating on stagnation line agrees very well with other calculations. Heating profiles along the body surface show rapid variation near the shoulder, which is related to the thinning of the boundary layer.

Reference 18 (July, 1993) is a first attempt at generalization of a non-equilibrium collisional-radiative (CR) plasma code to molecular plasmas. Details of the complex thermo-chemical model are presented. Simulations of shocks in nitrogen shows the importance of various coupling phenomena. New numerical technique for accurate convection of vibrational energies and multiple excited states is also described.

Reference 19 (June, 1993) is a study of ammonia ( $NH_3$ ) as an additive for reduction of  $NO_x$  emissions in a gas turbine, for the HSRP project. Zero-dimensional studies of the chemical kinetics are performed with two codes to provide an additional guarantee of the accuracy of solutions.

Research has also been in progress in the following areas, for which publications have not yet been written: The MOZART code has been upgraded and hydrocarbon chemistry routines are being developed and tested. A chemical equilibrium version of the MOZART code is being developed and tested. A delayed-equilibrium version of the MOZART code is being developed and tested. This involves development/test of the delayed-equilibrium option in the MOZART code. This option allows the replacement of complex chemical kinetics by a two-step mechanism. The first step is the calculation of a delay time counter, to reproduce the ignition delay of combustible mixtures (i.e., a time counter variable is convected and incremented accordingly). After ignition, the equilibrium chemistry is computed. This method has the advantage of being very fast for complex chemistry (HC), and is more accurate than the standard two-step models, which model the heat release approximately. The method has been compared with full kinetics calculations in cases of detonation propagation in  $H_2$ /air and  $C_3H_8$ /air mixtures, with very good results.

Theoretical analyses of implicit algorithms for electric field computations in two-fluid plasma simulations have been made. In preparation for the upgrading of the 2-fluid plasma code, research on faster algorithms has been done. Upgrading will proceed in the near future, and will include oscillatory RF field propagation and coupling.

Theoretical analysis of non-equilibrium turbulence models is under way. A careful review of current state-of-the-art turbulence models has been performed. A multi-scale (partitioning) model has been selected and will be implemented as first step.

A quasi-one-dimensional CFD code is under development for modelling the operation of two-stage light gas guns. This code is third-order accurate in space and second-order accurate in time. Near-exact Godunov solvers are used to obtain the fluxes at cell boundaries. Ideal-gas, Abel gas or dense media analytical or tabulated equations of state can be used.

The code models the burning of the gunpowder and two-phase flow of (unburned) gunpowder/gunpowder gas in the first stage of the gun. Skin friction and heat transfer between the powder and hydrogen (2nd-stage gas), piston and projectile and the tube walls is modelled. Early in 1994, radial conduction of heat in the tube walls and non-equilibrium turbulence in the gases will be added. The code will be proofed against measured piston and projectile velocities and pressure histories in guns. The code will be used to optimize performance of the guns in Ames' ballistic ranges and to guide development and testing of new gun operating techniques to decrease the stresses on the guns and the projectiles and to increase the launch velocities of the guns.

#### 4. Proposed New Experimental Techniques

Reference 20 (March, 1990) presents three new concepts to improve the performance of gas compression pump tubes for gas guns and shock tube drivers. The first concept involves the use of one or more diaphragms in the pump tube, thus replacing a single compression by multiple, successive compressions. The second concept involves a radical reduction in the length-to-diameter ratio of the pump tube. The third concept involves shock heating of the working gas by high explosives in a reusable device. Preliminary design analyses are performed on all three concepts and they appear to be quite feasible. These analyses predict that the new concepts offer substantial performance increases over conventional pump tubes.

Reference 21 (January, 1993) presents a new way to increase the stagnation pressure and enthalpy in shock tunnels. This technique involves the insertion of a properly profiled converging section in the driven tube of the facility. Using a one-dimensional inviscid full kinetics code, a number of different locations and shapes for the converging driven tube section were studied and the best cases found. For these best cases, for driven tube diameter reductions of factors of 2 and 3, the reservoir pressure can be increased by factors of 2.1 and 3.2, respectively and simultaneously, the enthalpy can be increased by factors of 1.5 and 2.1, respectively.

Reference 22 (to be published in early 1994) reviews scramjet combustor fuel injection and mixing enhancement techniques. Also, three new advanced mixing techniques are presented. The first is a combustor, curved so that buoyancy forces will aid in the penetration of the fuel across the combustor. The second is pulsation of the fuel injectors to increase penetration and mixing. A fluidic technique, a modified Hartmann-Sprenger tube, is identified as a strong candidate to generate the pulsations. The third is the injection behind pylons to allow deep penetration into the air stream. This technique is likely to produce high base pressures on the injector structure, particularly if base burning is encouraged. Curved or slanted pylons can be used to increase the recovery of fuel jet momentum. The paper assesses the potential of the new mixing techniques to increase scramjet engine performance.

#### 5. Wave and Detonation Scramjet Combustors

Reference 23 (July, 1989) is part of the oblique detonation wave engine (ODWE) concept research, and focuses on the design and analysis of the preliminary experiment performed in the 20 MW arc-heated tunnel at Ames. Calculations include fuel injection and mixing from struts. Shock pattern and fuel penetration/mixing are in good agreement with experiment. Reference 24 (September, 1989) was originally presented at the 9<sup>th</sup> International Symposium on Airbreathing Engines in Athens, Greece. This is an engineering study of the ODWE concept, with vehicle sizing and performance analysis, and comparison with conventional scramjet-powered vehicle. Reference 25 (1990) is a review paper of the ODWE work and includes an engineering study, a computational study and experimental results.

## 6. Pulsed Detonation Wave Engines

Reference 26 (July, 1988) is the group's first paper on pulsed detonation wave engines (PDE's); one-dimensional numerical simulations of a PDE and analyses of performance are given. The calculations demonstrate the operation and achievement of regular cycling at high performance operating conditions. Reference 27 (June, 1993) presents numerical simulation of a new hypersonic engine concept, where a PDE is used to supplement a scramjet engine at various stages of operation. Direct coupling between the two allows the use of pulsed blast waves from the PDE to stimulate mixing and combustion in the scramjet combustor. The resulting design (denoted by the acronym PDWA) is theoretically capable of higher performance than a simple scramjet. Simulations show the effectiveness of the PDE in enhancing mixing and combustion. Engineering aspects of the concept are also analyzed.

## 7. Ram Accelerator

Reference 28 (February, 1988) presents the basic ram accelerator concept, early theoretical models and experimental results. The projectile, which resembles the center body of a ramjet, travels through a tube filled with a premixed fuel-oxidizer-diluent mixture. The tube serves as the outer cowl of the ramjet. A straightforward, quasisteady, one-dimensional model of the acceleration process is presented. Results of recent experiments are also presented. The velocity range 0.7-1.5 km/sec has been explored in a 4.88-m long, 38-mm bore tube. Using methane, oxygen and various diluents, accelerations of up to 16,000 g have been achieved with 75 gm projectiles and gas fill pressures of 20 atm. Reference 29 (May, 1989) presents CFD calculations for three oblique detonation ram accelerator modes operating at velocities of 3.5 to 10.0 km/sec. The first drive mode achieves ignition on the reflection of the nose cone bow shock. The second drive mode relies on a sudden, steep, but small increase in projectile radius to initiate a detonation wave, following a deliberately gentle, gradual compression process. The third drive mode resembles the second mode except that the projectile is thermally protected by flying it through a core of pure hydrogen gas surrounded by a detonable mixture. CFD solutions are presented along with thrust levels, efficiencies and representative plots of the pressure field around the projectiles. These modes are found to provide good accelerations at velocities up to 10 km/sec.

Reference 30 (November, 1990) describes a new wall-mounted magnetic detector for measuring projectile passage times in tubes. The detector has the advantage of simplicity over laser and microwave techniques and has other advantages over the electrical contact wire technique. Representative data are presented. The detector is shown to be very insensitive to strong pressure waves and combustion, but able to detect the passage of the projectile (carrying one or two magnets) clearly. Reference 31 (July, 1991) presents the technique for initiating stable combustion in the thermally choked mode of ram accelerator operation. In this mode, subsonic combustion takes place behind the base of the projectile and leads to thermal choking, which stabilizes a normal shock system on the projectile, thus producing forward thrust. Operation of the ram accelerator is started by injecting the projectile into the accelerator tube at velocities of 0.7-1.3 km/sec by means of a conventional gas gun. A specially designed obturator, which seals the bore of the gun during this initial acceleration, enters the ram accelerator together with the projectile. The interaction of the obturator with the propellant gas ignites the gas mixture and establishes stable combustion behind the projectile.

Reference 32 (September, 1991) presents a theoretical and experimental investigation of the operational limits of the thermally choked ram accelerator. The results of experiments with 45-75 gm projectiles in a 12.2 m long accelerator tube, using methane-based propellant mixtures, are presented in the velocity range of 1.15-2.35 km/sec. Acceleration of projectiles with

staged propellants and transitions between different mixtures are investigated and the velocity limits in several propellant mixtures are explored. Agreement between theory and experiment is found to be very good. Reference 33 (March, 1992) presents a number of new concepts for a ram accelerator space launch system. The velocity and acceleration capabilities of a number of ram accelerator drive modes, including several new modes, are given. Passive (fin) stabilization during atmospheric transit is investigated and found to be promising. Gasdynamic heating in-tube and during atmospheric transit is studied; the former is found to be severe, but may be alleviated by the selection of the most suitable drive modes, transpiration cooling, or a hydrogen gas core. To place the payload in Earth orbit, scenarios using one impulse and three impulses (with an aeropass) and a new scenario involving an auxiliary vehicle are studied. The auxiliary vehicle scenario is found to be competitive regarding payload and requires a much simpler projectile, but has the disadvantage of requiring the auxiliary vehicle.

Reference 34 (September, 1993) presents a concept for ram acceleration which uses a combination of a gas core and a layer of solid explosive or propellant to generate high thrust densities. The concept can be either self-synchronized or externally synchronized, and may be reusable. It has the potential to achieve higher acceleration rates, higher exit velocities and lower tube lengths than the conventional premixed gas ram accelerator. Preliminary numerical simulations are presented and discussed; these solutions show the characteristics of the flow fields. Stable conditions were obtained for low mass loadings of solid explosive and relatively slow combustion. Reference 35 (to be published in 1994) presents a new end closure system for the ram accelerator. The ends of the main ram accelerator tube must have end closures which support substantial pressure differences. There are potentially serious difficulties using solid end closures such as diaphragms pierced by the projectile or explosively removed end closures or fast acting valves. These include risks of significant damage to the projectile and launch tube and the wasting of tube length. A new end closure system which uses the momentum of an annular axial air jet to support the required pressure differences is described. A preliminary design of such an air jet end closure is presented and it is concluded that the requirements for air flow rates and storage are reasonable and would likely add only a modest increase to the overall cost of the launch system.

## 8. Gas Optics

Reference 36 (September, 1989) presents theoretical and experimental results on a (negative) vortex gas lens. Such a lens has a potential power density capability of  $10^9$ - $10^{10}$  w/cm<sup>2</sup>. An experimental prototype was constructed and the divergence half angle of the exiting beam was measured as a function of the lens operating parameters. Reasonably good agreement is found between the experimental results and theoretical calculations. The expanded beam was observed to be steady and no strong, potentially beam-degrading jets were found to issue from the ends of the lens.

## References

1. H. A. Zambrana and W. Johanson, "Using a Graphical Programming Language to Write CAMAC/GPIB Instrument Drivers," presented at the 37th International Instrumentation Symposium, San Diego, CA, May 5-9, 1991. (Also published as NASA Technical Memorandum 103849, 1991.)
2. D. W. Bogdanoff, G. S. Deiwert, A. W. Strawa and J. A. Cavolowsky, "Ames Shock Tunnel Facility Calibration and Initial Test Results," Paper 80, presented at the Seventh NASP Symposium, NASA Lewis Research Center, Cleveland, OH, October 23-27, 1989.
3. D. W. Bogdanoff, J. A. Cavolowsky, C. Park and G. S. Deiwert, "Ames 16 Inch

- Shock Tunnel Performance Characteristics and Diagnostic Capabilities for High Speed Combustors,” Paper 112, presented at the Ninth NASP Symposium, Naval Training Center, Orlando, FL, November 1-2, 1990.
4. J. A. Cavolowsky, D. W. Bogdanoff and R. K. Hanson, “Test and Diagnostic Capability for High Mach Number Propulsion Testing in the Ames Pulse Facility” Paper 254, presented at the Tenth NASP Symposium, Monterey, CA, April 23-26, 1991.
  5. D. W. Bogdanoff, H. A. Zambrana, J. A. Cavolowsky, M. E. Newfield, C. J. Cornelison and R. J. Miller, “Reactivation and Upgrade of the NASA Ames 16 Inch Shock Tunnel,” AIAA Paper 92-0237, presented at the 30th Aerospace Sciences Meeting, Reno, NV, January 6-9, 1992.
  6. M. P. Loomis, H. A. Zambrana, D. W. Bogdanoff, T. C. Tam, J. A. Cavolowsky, M. E. Newfield and R. D. Bittner, “30 Degree Injectors at Mach 14 and 16 Enthalpies,” AIAA Paper 92-3288, presented at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Nashville, TN, July 6-8, 1992.
  7. J. A. Cavolowsky, M. P. Loomis, D. W. Bogdanoff, H. A. Zambrana, M. E. Newfield and T. C. Tam, “Flow Characterization in the NASA Ames 16-Inch Tunnel,” AIAA Paper 92-3810, presented at the 28th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Nashville, TN, July 6-8, 1992.
  8. D. W. Bogdanoff, G. Wilson, C. Park and M. Sussman, “Options for Upgrade of Ames 16 Inch Shock Tunnel,” to be presented at the AIAA 32nd Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.
  9. S.-H. Lee, D. W. Bogdanoff, J. A. Cavolowsky and C. Park, “Nonequilibrium H<sub>2</sub>-Air Reactions in Shock Tunnel Nozzles,” Paper AIAA-90-1751, presented at the AIAA/ASME 5th Joint Thermophysics and Heat Transfer Conference, Seattle, WA, June 18-20, 1990.
  10. J.-L. Cambier, S. Tokarcik and D. Prabhu, “Numerical Simulation of Unsteady Flow in a Hypersonic Shock Tunnel Facility,” AIAA paper 92-4029, presented at the 17<sup>th</sup> AIAA Ground Testing Conference, Nashville, TN, July 1992.
  11. S. Polsky and J.-L. Cambier, “Numerical Study of the Transient Flow in the Driven Tube and the Nozzle Section of a Shock Tunnel,” AIAA paper 93-2018, presented at the 29<sup>th</sup> AIAA Joint Propulsion Conference, Monterey, CA, June 28-30, 1993.
  12. J.-L. Cambier and G. P. Menees, “A Multi-Temperature TVD Algorithm for relaxing Hypersonic Flows”, Paper 89-1971, presented at the 9<sup>th</sup> AIAA CFD Conference, Buffalo, NY, June, 1989.
  13. D. W. Bogdanoff and D. C. Brackett, “Godunov Computational Fluid Dynamics Method for Extreme Velocities and Any Equation of State,” *AIAA Journal*, Vol. 27, pp. 909-917, July 1989.
  14. J.-L. Cambier, “Numerical Methods for TVD Transport and Coupled Relaxing Processes in Gases and Plasmas”, Paper 90-1574, presented at the 21<sup>st</sup> Fluid Dynamics, Plasma Dynamics and Lasers Conference, Seattle, WA, June 1990.
  15. J.-L. Cambier, “Numerical Simulations of a Nonequilibrium Argon Plasma in a Shock-Tube Experiment”, Paper 91-1464, presented at the AIAA 22<sup>nd</sup> Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, HI, June 1991.
  16. J.-L. Cambier and D. Prabhu, “Numerical Simulations of Nonequilibrium Shock Layers with a Highly Efficient Implicit Scheme”, Paper 92-2973, presented at the 23<sup>rd</sup> AIAA Plasma Dynamics and Lasers Conference, Nashville, TN, July 1992.

17. J.-L. Cambier and M. Tauber, "Computations of Nonequilibrium Shock Layers for the Comet Sample Return Vehicle," Paper 93-2863, presented at AIAA 28<sup>th</sup> Thermophysics Conference, Orlando, FL, July 6-8, 1993.
18. J.-L. Cambier and S. Moreau, "Numerical Simulation of a Molecular Plasma in Collisional-Radiative Nonequilibrium," Paper 93-3196, presented at the 24<sup>th</sup> AIAA Plasma Dynamics Conference, Orlando, FL, July 6-9, 1993.
19. H. G. Adelman, G. P. Menees and J.-L. Cambier, "NO<sub>x</sub> Reduction Additives for Aircraft Gas Turbines Engines," Paper 93-2594, presented at the AIAA 29<sup>th</sup> Joint Propulsion Conference, Monterey, CA, June 28-30, 1993.
20. D. W. Bogdanoff, "Improvement of Pump Tubes for Gas Guns and Shock Tube Drivers," *AIAA Journal*, Vol. 28, pp. 483-491, March 1990.
21. D. W. Bogdanoff and J.-L. Cambier, "Increase of Stagnation Pressure and Enthalpy in Shock Tunnels," AIAA Paper 93-0350, presented at the 31st AIAA Aerospace Sciences Meeting, Reno, NV, January 11-14, 1993.
22. D. W. Bogdanoff, "Advanced Injection and Mixing Techniques for Scramjet Combustors," to be published in the *Journal of Propulsion and Power*.
23. H. G. Adelman, J.-L. Cambier and G. P. Menees, "Experimental and Analytical Investigations of Wave Enhanced Supersonic Combustors," Paper 89-2787, presented at the AIAA 25<sup>th</sup> Joint Propulsion Conference, Monterey, CA, July 1989.
24. G. P. Menees, H. G. Adelman, J.-L. Cambier and J.V. Bowles, "Wave Combustors for Trans-Atmospheric Vehicles," *Journal of Propulsion and Power*, Vol. 8, p. 709 (1992).
25. G. P. Menees, H. G. Adelman and J.-L. Cambier, "Analytical and Experimental Investigations of the ODWE concept", Paper CP-479, Proceedings of AGARD Meeting on Hypersonic Combined Cycle Propulsion, Madrid, Spain, 1990.
26. J.-L. Cambier and H. G. Adelman, "Preliminary Numerical Simulations of a Pulsed Detonation Wave Engine", Paper 88-2960, presented at the AIAA 24<sup>th</sup> Joint Propulsion Conference, Boston, MA, July 1988.
27. J.-L. Cambier, H. G. Adelman and G. P. Menees, "Numerical Simulation of a Pulsed Detonation Wave Augmentor Device," Paper 93-1985, presented at the 29<sup>th</sup> AIAA Joint Propulsion Conference, Monterey, CA, June 28-30, 1993.
28. A. Hertzberg, A. P. Bruckner and D. W. Bogdanoff, "Ram Accelerator: A New Chemical Method of Achieving Ultrahigh Velocities," *AIAA Journal*, Vol. 26, pp. 195-203, February 1988.
29. D. C. Brackett and D. W. Bogdanoff, "Computational Investigation of Oblique Detonation Ramjet-in-Tube Concepts," *Journal of Propulsion and Power*, Vol. 5, pp. 276-281, May-June 1989.
30. D. W. Bogdanoff, C. Knowlen, D. Murakami and I. Stonich, "A Magnetic Detector for Projectiles in Tubes," *AIAA Journal*, Vol. 28, pp. 1942-1944, November 1990.
31. A. P. Bruckner, E. A. Burnham, C. Knowlen, A. Hertzberg and D. W. Bogdanoff, "Initiation of Combustion in the Thermally Choked Ram Accelerator," presented at the 18th International Symposium on Shock Waves, Sendai, Japan, July 21-26, 1991.
32. A. P. Bruckner, C. Knowlen, A. Hertzberg and D. W. Bogdanoff, "Operational Characteristics of the Thermally Choked Ram Accelerator," *Journal of Propulsion and Power*, Vol. 7, pp. 826-836, September-October 1991.
33. D. W. Bogdanoff, "Ram Accelerator Direct Space Launch System - New Concepts,"

- Journal of Propulsion and Power*, Vol. 8, pp. 481-490, March-April 1992.
34. J.-L. Cambier and D. W. Bogdanoff, "Ram Acceleration from a Two-Phase Detonative System," presented at the First International Workshop on Ram Accelerator, Saint-Louis, France, September 7-10, 1993.
  35. D. W. Bogdanoff, "New End Closure System for the Ram Accelerator," to be published in the *Journal of Propulsion and Power*.
  36. D. W. Bogdanoff, A. Berschauer, T. W. Parker and J. E. Vickers, "The Vortex Gas Lens," *Applied Optics*, Vol. 28, pp. 3960-3967, September 15, 1989.

#### Appendix

This appendix includes all publications from July, 1993 onwards with one exception, explained below. The relevant references are Refs. 8, 17, 18, 22, 34 and 35. Copies of these references, except for Ref. 8, follow. Reference 8 includes competitively sensitive material and can not be included at this time. The sensitive material will be deleted from Ref. 8 and a copy can be supplied later in December, 1993, if required.